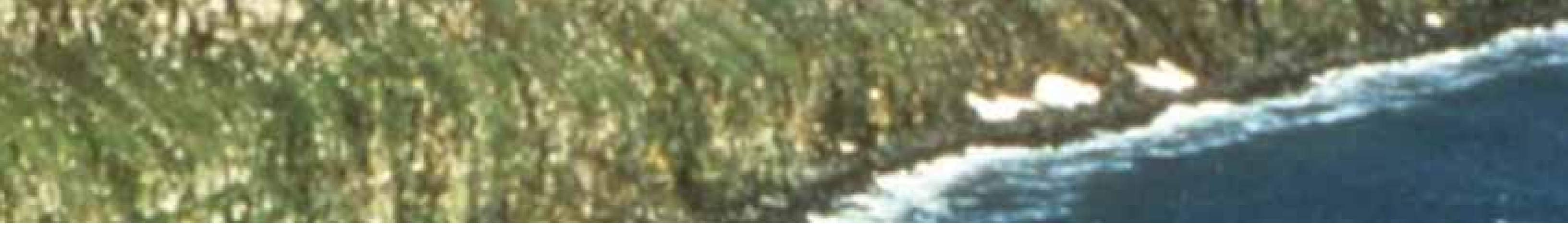
Using Hi-res Acoustics to VAMP Up Better Estimates of Methane Hydrate Concentrations

Researchers have long speculated that the Bering Sea contains quantities of methane gas hydrates (found only in deep water and in permafrost) vast enough to constitute a potentially game-changing energy source. Key to discerning the concentrations of these "fire in the ice" clathrates is using underwater acoustics to sense sound speed anomalies (velocity-amplitude anomalies or VAMPs) in the Bering Sea's thick sediment columns — where there are VAMPs, there is methane gas and methane hydrate. In August 2011, a U.S. Geological Survey-led team, of which the Naval Research Laboratory is an important member, applied the latest high-resolution acoustic sensing technology to extensively survey the remote and largely unexplored Bering Sea, specifically targeting the VAMPs. The team gathered high-quality data that not only confirm the presence of gas and gas hydrates in the deep-ocean basin of the central Bering Sea, but that also will allow quantitative estimates to be made of the concentrations of those hydrates in the upper few hundred meters of sediment.

Methane hydrates were first detected in the Bering Sea as a consequence of the acoustic mapping done as part of the anti-submarine warfare exercises during the Cold War — seems that the potentially hottest new energy source is a Cold War bonus.



Deep-Water Acoustic Anomalies from Methane Hydrate in the Bering Sea

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A recent expedition to the central Bering Sea, one of the most remote locations in the world, has yielded observations confirming gas and gas hydrates in this deep ocean basin. Significant sound speed anomalies found using inversion of pre-stack seismic data are observed in association with variable seismic amplitude anomalies in the thick sediment column. The anomalously low sound speeds below the inferred base of methane hydrate stability indicate the presence of potentially large quantities of gas-phase methane associated with each velocity-amplitude anomaly (VAMP). The data acquired are of such high quality that quantitative estimates of the concentrations of gas hydrates in the upper few hundred meters of sediment are also possible, and analyses are under way to make these estimates. Several VAMPs were specifically targeted in this survey; others were crossed incidentally. Indications of many dozens or hundreds of these features exist throughout the portion of the Bering Sea relevant to the U.S. extended continental shelf (ECS) consistent with the United Nations Convention on the Law of the Sea.

THE BERING SEA — ONE OF THE LAST FRONTIER OCEAN BASINS

In August 2011, a U.S. Geological Survey (USGS)-led team including the Naval Research Laboratory (NRL), the National Oceanic and Atmospheric Administration (NOAA), and other agencies and universities acquired state-of-the-art multichannel seismic data, ocean bottom seismometer (OBS) data, and Navy sonobuoy data, dramatically improving our knowledge of the scantly surveyed Bering Sea. The Bering Sea is approximately 50% larger in area than the Gulf of Mexico, and consists of the wide Beringian Shelf in the north and east, and the Aleutian Basin in the south and west (Fig. 1), which contains an unusually thick sediment column for a deep (3800 m) basin. It is this thick sediment column that has prompted investigations such as the one described here, the funded purpose of which was to assess the potential to define a U.S. extended continental shelf (ECS) maritime zone under the United Nations Convention on the Law of the Sea (UNCLOS). The survey was designed to collect long-offset reflection and refraction seismic data. These data are also very useful for constraining the locations and concentrations of methane gas and methane hydrate — the ice-like combination of methane and water that exists only in deep water (greater than about 350 m) or in permafrost settings.

The area surveyed was the isolated area of international waters (known as the "donut hole" between the United States and Russia) in the Aleutian Basin portion of the Bering Sea, located north of the Aleutian island chain and east of Kamchatka (Fig. 1). Velocity-amplitude anomalies (VAMPs) were first seen in this area in seismic data acquired in 1972 by the U.S. Naval Oceanographic Office off the USNS *Bent*.[1] Several investigations prior to this (e.g., Ref. 2) reported no such anomalies. The data analyzed by Scholl and Cooper[1] allowed first estimates of numbers of these features, their physical character, and their possible association with methane and methane hydrate. Later, in the 1980s, digital seismic data were acquired in this area, allowing significantly improved analysis of the geometry of these features.[3] Particularly intriguing was the number and size of the VAMPs — hundreds of them, up to 5 km across, and potentially holding significant quantities (up to 1 trillion cubic feet, or TCF) of natural gas.[4,5] Despite exceedingly careful and unconventional processing techniques, the older data lacked sufficient offset range to analyze the sound speeds with sufficient

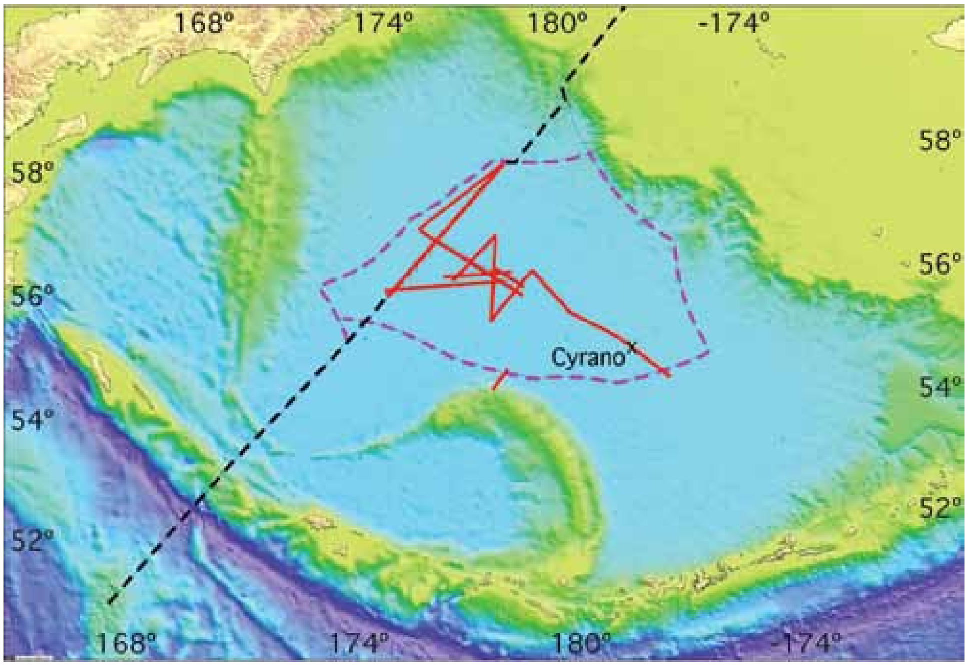

FIGURE 1
The Bering Sea contains an area (the "donut hole," dashed purple curve) of international waters surrounded by the exclusive economic zones (EEZs) of the United States and Russia. The dashed black curves represent the negotiated U.S.–Russia border, and red curves represent seismic and other data acquisition lines acquired in the 2011 survey.

accuracy to distinguish gas and gas hydrate concentrations within the VAMPs.

The new 2011 data shed a bright new light on these features. The data were acquired using the R/V *Marcus G. Langseth*, a ship designed for high-powered, accurate seismic investigation, with an 8 km, 640-channel streamer and a 6600 cu. in., 36-airgun source array. Ocean bottom seismometers and Navy sonobuoys augmented the normal incidence data with ultra-long-offset (60 to 80 km) seismic data. The acquisition program was specifically designed to maximize the sediment sound speed accuracy, with OBS data providing detailed P- and S-wave velocity structure in the sediments and upper crust.

These phenomenal new, long-offset, multichannel data are ideally suited to analyze distribution and concentration of methane and methane hydrate in the upper 1 km of Bering Sea sediment. Although a thick sediment column is generally required to generate the methane required to supersaturate the pore fluids with respect to methane, the methane hydrate concentrates methane in the shallower section. The anomalously low sound speed of methane and anomalously high sound speed of methane hydrate can impact deep-water acoustic bottom-loss and reverberation, but these anomalous sound speeds can also be used diagnostically to analyze the distribution and to some extent the concentration of free gas and gas hydrate in these deep-water settings.

A seismic image of one of the VAMPs using the new data is shown in Fig. 2 (note the vertical exaggeration, and gain change at 5.2 km). This feature is about 4 km wide and is associated with anomalous reflectivity all the way through the sediments and into an elevated block of basement rock (likely top of oceanic crust) at about 7.8 km depth. Reflections from the top of the surrounding oceanic basement occur between about 8.6 and 9.0 km. The VAMPs are similar in shape to seismic chimneys (e.g., Ref. 6), which are also seen in this area (arrows in Fig. 2), but the VAMPs are at least an order of magnitude larger. Like chimneys, they appear to be associated with near-vertical faulting. In the case of the VAMPs, the underlying faults, or at least sharp folds of sediments, appear to be associated with changes in basement relief. It may be that the fluid flux that transports the methane is most active during episodes of tectonic activity. The VAMP in Fig. 2 is associated with a particularly large basement block informally called "Cyrano's nose."

WHY ARE MULTICHANNEL SEISMIC DATA AND SPECIAL PROCESSING TECHNIQUES IMPORTANT?

Multichannel data provide direct measurements of sound speed. Conventional seismic data processing methods are adequate for estimating sediment thick-

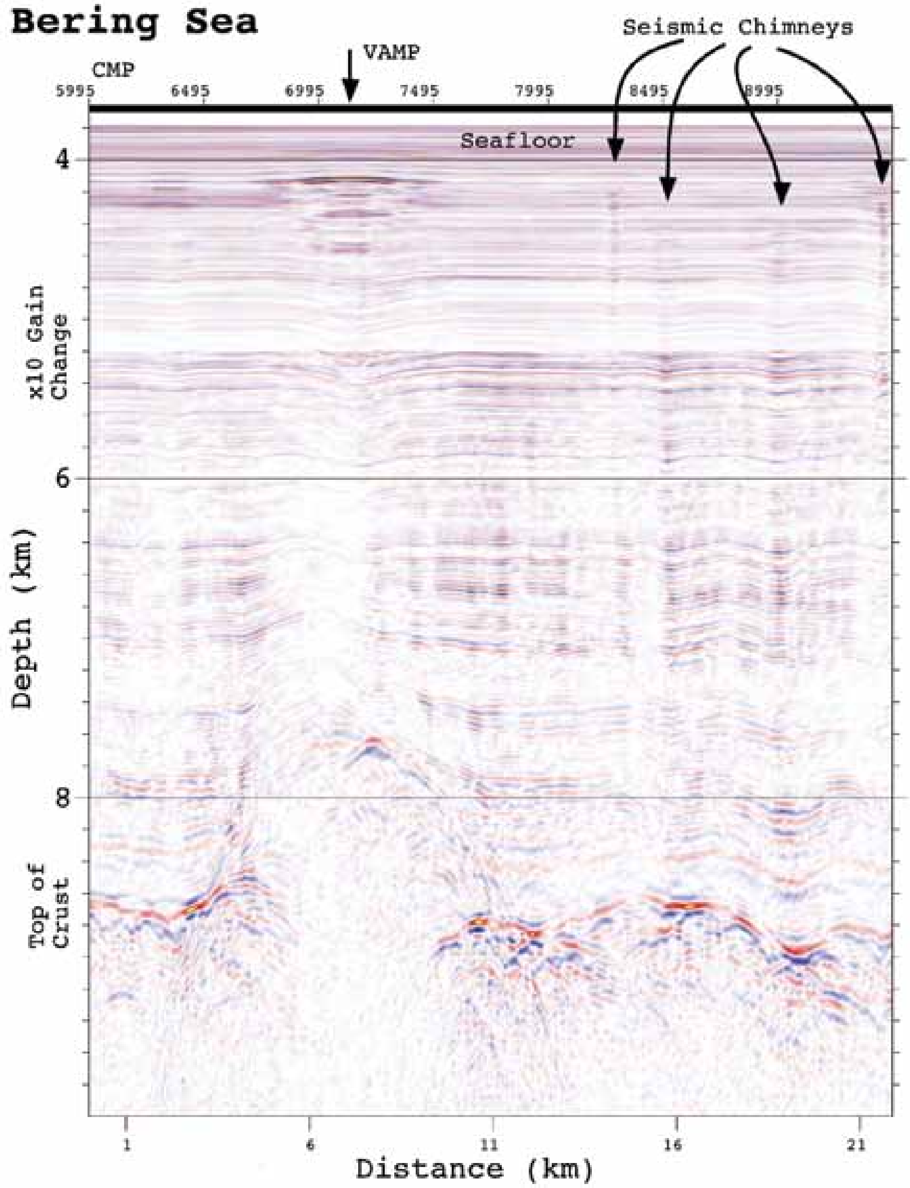

FIGURE 2
This example of a VAMP lies over an elevated basement high, informally called "Cyrano's nose," in the middle portion of the Aleutian Basin. Seismic data are displayed here with peaks and troughs of the seismic reflection colored blue and red, respectively. High amplitudes are displayed with bolder colors; clipped positive and negative events are black and yellow, respectively. The brightest feature of the VAMP is the negative reflection at about 4.1 km depth.

ness in this basin, but the *Langseth* data are of such high quality that careful processing can yield seismic images and velocities that are uncharacteristically accurate for these water depths (~4 km). Figure 3(a) shows a common midpoint (CMP) seismic reflection gather. Only a portion near the seafloor is shown to emphasize the curvature of the individual reflection events. Each column or trace in the CMP corresponds to a single source-receiver pair. The traces in this gather are the source-receiver pairs whose midpoints fall within a single 6.25 m wide bin — essentially forming up to 80 individual seismic records at every point along a vertical line into the seafloor. There are thousands to tens of thousands of CMP bins per line, every 6.25 m.

Because the seismic energy at long source-receiver offsets travels through more sediment than at shorter source-receiver offsets, the difference in arrival time as a function of offset for a single reflection (curvature of the events in Fig. 3(a)) can be used to measure sediment sound speed. The earlier, single-channel data had no such sound speed information. Once the sediment sound speed (P-wave velocity, or just velocity) is known,

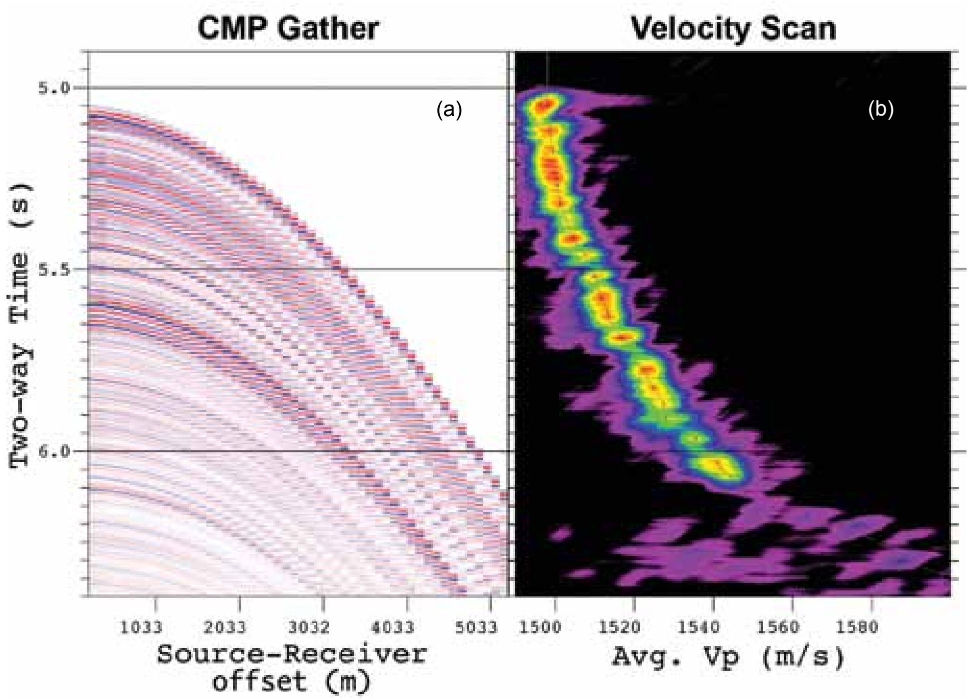

FIGURE 3
(a) This common midpoint (CMP) gather is composed of seismograms corresponding to a single vertical reflection point on the seafloor. This particular CMP occurs at the left edge of the seismic profile shown in Fig. 4. The large source-receiver offsets correspond to large angles of incidence, longer path lengths, and, therefore, longer arrival times. (b) The curving events in Fig. 3(a) are matched with theoretical trajectories calculated with a range of the root-mean-square (rms) average velocities from the sea surface to each point below the seafloor. Semblance peaks marked with small crosses (warm colors, relative amplitude) correspond to good matches, forming a curve of travel-time vs rms velocity (fine curve connecting semblance peaks).

the depth to any seismic reflection can be estimated. The velocity profile can also be used to straighten the curved trajectories seen in Fig. 3(a) such that they can be added together or stacked. This increases the signal-to-noise ratio, resulting, for example, in the very high quality stacked image shown in Fig. 2.

One aspect of what makes the new Bering Sea data and analysis unique is the detail to which these reflection trajectories can be analyzed. The semblance is a measure of coherency of a reflection with respect to offset. Figure 3(b) shows a semblance plot calculated at every time sample (0.002 s intervals) in the CMP gather from 4.9 to 6.8 s two-way time, and with a velocity increment of 0.1 m/s — a much finer time and velocity spacing than is ordinarily used. The CMP used in Fig. 3(b) comes from the far left edge of the section shown in Fig. 4, away from the large anomaly associated with the VAMP. Warm colors in Fig. 3(b) correspond to semblance peaks — the amplitude scale is relative. Bright spots in the semblance plot correspond to travel time trajectories that are coherent, and therefore indicate the arrival time and the root-mean-square (rms) average velocity from the sea surface down to that reflector. The change in rms average velocity between two interfaces can be inverted to yield an instantaneous or interval velocity that is diagnostic of the material that makes up the layer, or interval between the interfaces.[7] The uncertainty in the interval velocity calculation increases with depth and is inversely proportional to layer thickness.[8] More accurate average velocity analyses result in higher accuracy interval velocities (better diagnostics) for thinner layers (higher resolution).

Another aspect of what makes this analysis noteworthy is the use of an automated velocity inversion, allowing consistent analysis for *each* CMP. Practical inversion for interval velocity is inherently unstable, and is almost always done by an interpreter. Hand interpretation is time consuming and may therefore only be applied on one out of every hundred or several hundred CMPs.

The earth model in the inversion developed and used here consists of interfaces picked on the basis of maximum semblance (small crosses on the semblance peaks in Fig. 3(b)), and a linear gradient of instantaneous velocity between the interfaces. The two-way times are fixed, and the velocity gradients are inverted for globally (all at the same time) using the technique of very fast simulated annealing (VFSA).[9] The cost function, or fitness function, for each attempted model consists of the sum of the absolute difference in average velocity at each interface, so the average velocity profile derived from the interval velocity gradients is always checked against the measured average velocity of the semblance plot and penalized for straying too far.

Stability in the automated inversion process is achieved by inverting for interval velocity gradients, not actual interval velocities. Inverting directly for interval velocities of sediment layers that are completely independent tends to result in oscillating over- and underestimate of interval velocity, while still resulting in a similar, overall average velocity. Because the gradient in each layer depends on the interval velocity at the top and bottom of each layer, the gradient of each layer is linked to the gradients of the layer above and below. Starting with a known interval velocity for the water column, and known travel times to each interface, interval velocities can be calculated from the gradients.

This method effectively smooths the interval velocity profile and mitigates the problem of alternating over-and underestimate of interval velocity. An example of the average velocity profile obtained from this technique is shown in Fig. 3(b). The fine curve connecting the semblance peaks corresponds to the rms average velocity calculated from the interval velocity gradients in the model.

Figure 4(a) shows a blow-up of the Cyrano VAMP, but depth converted with the velocity profiles obtained through VFSA at each CMP. The velocity field was smoothed before depth conversion. Figure 4(b) shows the velocity field before smoothing to illustrate the level of noise (instability) still present in the analysis — the instabilities have been mitigated, but not eliminated entirely. Because of the high wavenumber instabilities, only the low wavenumber, background trend in Fig. 4(b) can be attributed to actual geological character.

WHAT THE NEW DATA SAY ABOUT GAS AND GAS HYDRATE

The dominant characteristic of the VAMPs is their variable amplitude. The very bright reflectivity of the top of the VAMP in Fig. 4(a) at 4.1 km suggests an accumulation of gas has built up at this location, almost certainly methane gas, and very likely capped by methane hydrate–filled pore space. Methane hydrate is stable only at high pressures and low temperatures and would be expected at these sediment and water depths given high enough concentrations of methane (supersaturation). The base of gas hydrate stability (BGHS) in the sediments is a pressure–temperature boundary that forms an upper limit of where free methane gas can exist in the sediment. Where gas accumulates below this boundary, a bottom-simulating reflector (BSR) can be observed in seismic data.

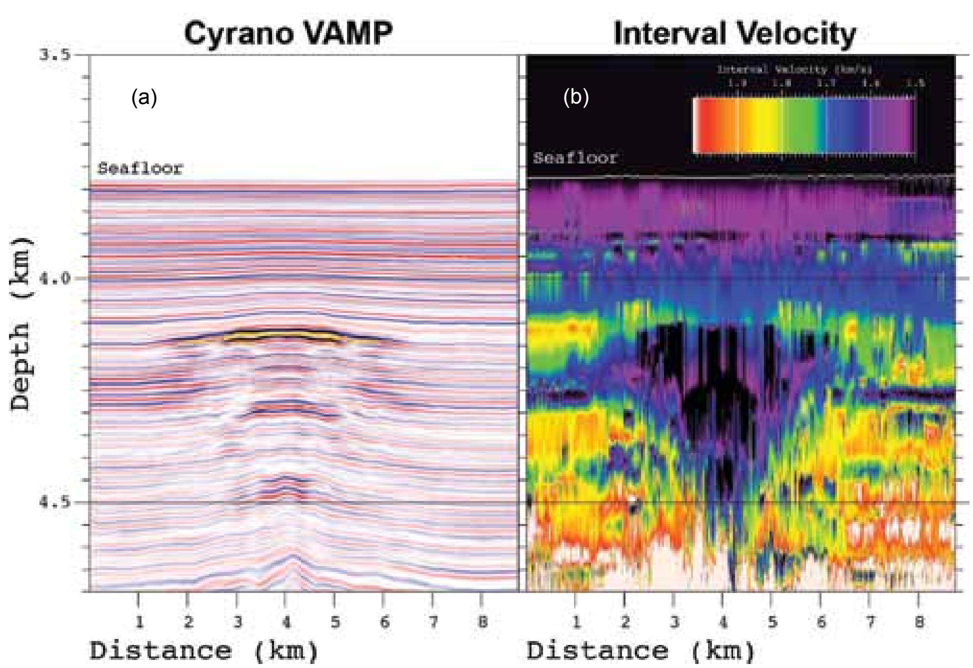

FIGURE 4
(a) The Cyrano VAMP is shown here in a true amplitude stacked section. Note the bright reflectivity of the bottom-simulating reflector (BSR) at about 4.1 to 4.15 km depth over the VAMP, the depth expected for the base of gas hydrate stability (BGHS). (b) The interval (instantaneous) velocity field over the Cyrano VAMP shows the low velocity anomaly (cooler colors) caused by free methane gas. Interfaces were not picked by hand, but rather correspond to the brightest, most coherent seismic reflections.

The depth of the bright reflection over the VAMP in Fig. 4(a) is at 4.1 km, or about 330 m below the seafloor. Using the gas hydrate stability curve of Brown et al.,[10] and a bottom water temperature of 1.6 °C (as measured on a CTD [conductivity, temperature, depth] cast to the bottom in this area on the 2011 cruise)[11] results in a geothermal gradient of 66 mK/m over the VAMP. This value is somewhat high for a tectonically passive area such as the Aleutian Basin, but not inconsistent with thermal gradients of about 55 mK/m measured in this area,[12] possibly due to its back-arc tectonic setting.[13] In areas of fluid flux, a higher heat flux is expected, therefore the bright reflection in Fig. 4(a) likely coincides with the base of methane hydrate stability and is likely a BSR associated with increased fluid and methane gas flow at this location.

The BSR at the top of the VAMP corresponds exactly with the top of the low velocity anomaly shown as black (slower than 1500 m/s) in Fig. 4(b), and contrasts with the expected velocities of 1700 to 1900 m/s seen at the edges of Fig. 4(b). The low velocity zone is tapered downward, suggesting that most gas responsible for the anomaly is located at the top — the BGHS — and trapped by pore-filling gas hydrate. Further, there is a laterally very consistent low velocity zone at about 4.25 km depth or about 475 m below the seafloor. This corresponds to a geothermal gradient of about 47 mK/m away from the VAMP, and is also consistent with the BGHS, but in a lower flux setting than at the top of the VAMP.

Because free gas creates a much stronger negative anomaly than gas hydrate makes a positive anomaly, the free gas will always be easier to detect. Although we would expect to see a positive interval velocity anomaly associated with the gas hydrates above the VAMP, no such anomaly is seen in the velocity inversion for this VAMP. This could mean that the hydrate concentration above the VAMP is only a few percent of the pore space, or that a gas hydrate enriched layer falls below the resolution of even this relatively high-resolution technique. Depending on the concentration, such a layer would have to be less than 5 to 10 m thick to avoid our detection.

GREATER SIGNIFICANCE

The data acquired in August 2011 confirm the thick (4 to 5 km) sediment column throughout the deep Bering Sea. There are many conventional seismic chimneys in the area, suggesting active fluid flux for at least several periods in the sedimentary history of the basin. We now have the data and processing techniques (inversion for diagnostic sound speeds) to improve the estimates of gas and gas hydrate concentrations in this and other deep-water settings. Of the hundreds of super-chimneys — VAMPs — in the Aleutian Basin, the few analyzed to date all indicate zones of significantly reduced P-wave velocity, for which the only reasonable explanation is free methane gas. The size and number of the VAMPs suggests there may be significant quantities of gas and gas hydrate in this still underexplored basin.

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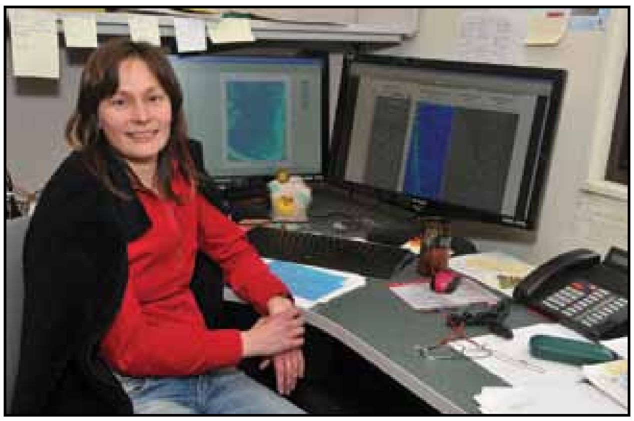

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